“Teegi’s so Cute!”: Assessing the Pedagogical Potential of an Interactive Tangible Interface for Schoolchildren

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Figure 1: Teegi surrounded by the children who took part in the study

ABSTRACT

Cerebral activity is an intangible physiological process that is difficult to apprehend, especially for children. To overcome this difficulty, Teegi was designed as a new type of educational support. This tangible interface enables children to discover the relationship between brain activity and the functions of the human body. We developed a multi-methods research approach to estimate the pedagogical potential of Teegi used in a real-life educational context. Using this interdisciplinary methodology, we conducted a user study (N=29) that highlighted the strengths of this interface, both in terms of its usability and its impact on learning. Moreover, results revealed possible improvements to further increase pedagogical effectiveness. This type of interface, as well as the evaluation method that we propose, contribute to extending our knowledge concerning the pedagogical use of new interactive tools at school.

Author Keywords

Pedagogical potential assessment; School context; Tangible User Interface (TUI); Education; Brain functions; Child-Computer Interaction; Usability testing; Collaboration.

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INTRODUCTION

Designing Tangible User Interfaces (TUIs) specifically for children is a recent research direction that holds great prospects for both formal and informal education [14; 24; 29; 55; 58; 74; 77] (*n.b.* according to the Piaget’s stages of development [50; 52], the children refereed in this paper are 7-11 years old). A considerable number of reviews highlight the promise of TUIs for improving learning, for example by enabling collaboration, hands-on learning approach, the physical manipulation of objects that are relevant to the task, or by the added value of digital features that could decrease the abstract level of the contents to grasp (see for instance [11; 16; 27; 39; 57; 59; 79; 81]). Although TUIs hold great promise for pedagogical innovation, there is still a lack of empirical evidence to assume their benefits [78], especially towards quality of learning in real context of use. Consequently, the impact of such approaches in formal/informal education is still unclear, and experiments need to be conducted.

In this study, we tested with schoolchild participants the relevance of a pedagogical TUI, which is the new version of Teegi (see Figures 1 & 2). This TUI was designed for introducing simple concepts of brain functions to a wide audience [21]. Teegi is a physical animated puppet that is easy to manipulate. He was designed to help users discover by themselves, in a hands-on approach, brain structure and the areas associated with particular functions: vision and motor control of the hands and feet.

Figure 2: Teegi displays the brain areas involved in vision and motor control of the hands and feet. In order to display these areas, users directly manipulate Teegi's hands and feet, or close his eyes [21].

Cerebral activity is an intangible physiological process that is difficult to apprehend for children. With Teegi, we aim at providing an adapted pedagogical TUI to pupils, to help them to discover the relationship between brain activity and the functions of the human body in formal/informal learning contexts. In this paper, we first recall how the new version of Teegi works and describe the needs this version caters for. Next, we investigate the pedagogical potential of this interactive device for pupils during a science school outing.

In educational contexts, the learning benefits are directly related to the effective activities implemented to achieve the instruction goals (knowledge and/or skills), depending on the context of use. Probably because such studies are very complex to implement and are therefore rather scarce, studies that assess the pedagogical relevance of TUI in real context of school use remain uncommon [9; 11; 17; 34; 56]. What is more, standard HCI assessment tools such as questionnaires are often of limited value in this context and do not cover all the qualities to appraise. By combining Human-Computer Interaction (HCI) and learning sciences, this paper aims also to complete the standard Child-Computer Interface (CCI) assessment methods and tools that can be used in schools. We designed a multidisciplinary, qualitatively driven multimethod approach to assess the pedagogical potential provided by Teegi in real context of use. Beyond the results, which evidence for example that TUI's pedagogical potential could be impacted by the group size, the paper's contributions remain on i) the detailed design of the user-learner study conducted in a real-life context of use to facilitate reproduction; ii) the inclusion of assessment tools from the field of learning sciences which allow us to measure not only usability and desirability of the interface, but also the effects of this TUI on learning and learning processes.

TEEGI

Teegi is a physical puppet upon which the areas of the brain involved in vision and motor control of the hands and feet are displayed. The first version of Teegi [20] relied on electroencephalography (EEG) to display the user's real-time brain activity and was tested with adults in laboratory conditions. This second version of Teegi [21] was designed for public awareness without having to use a brain activity acquisition system. The goal of this TUI is then to render these complex physiological functions easy to explore and tangible, that is to say undeniably real. It provides interactive elements which allow users to learn about brain function by directly manipulating the puppet. It is this *"standalone"* version (see Figure 2) that we tested in a learning environment with primary school pupils, in order to estimate its potentiality towards this specific public.

Teegi is autonomous and does not need to be connected to any external device. Teegi's 3D printed body contains a Raspberry Pi3, which controls the display and the sensors, and NiMH batteries which provide an operating life of approximately 2 hours. His head is a semi-spherical display comprising 402 light-emitting diodes (LEDs – Adafruit Neopixels). Their light is diffused by Teegi's 3 mm-thick acrylic glass helmet. Two 8x8 matrices of white LEDs represent Teegi's eyes. His eyes can be "closed" by pressing a button in their center. Doing so makes an area at the back of Teegi's head light up in color. This represents the human occipital cortex, which includes the primary visual cortex. Indeed, this reflects the major change in brain activity that occurs when the eyes are no longer solicited, and the neurons of this area "synchronize" in the absence of stimuli. Teegi's hands and feet are connected to servo motors (Dynamixel XL320) which can operate either as input or output mechanisms. When working as output mechanisms, they allow Teegi to move his limbs automatically. This mode was used at the beginning of the experiment to demonstrate the various possible interactions to the children. On the other hand, when working as input mechanisms (Teegi's default mode) the motors allow users to discover which brain areas are associated with different movements by manipulating Teegi's limbs. Thus, if a user moves Teegi's left hand, an area located "in the middle on the right" of Teegi's head lights up. This area represents the human primary motor cortex and the parietal area. Moving Teegi's right hand causes the opposite side of his head to light up, since the brain hemispheres control the contralateral side of the body. Finally, manipulating Teegi's feet causes the "top" of his head to light up. This is consistent with the somatotopic arrangement of the primary motor cortex [48].

Contextualizing the pedagogical needs

Many events worldwide aim to bring attention to brain science advances (*e.g.* "brain awareness week" see https://www.sfn.org/baw/). Directed at the general public, most events include children at school or during scientific workshops. One goal is to encourage the pupils to discover the brain functions. Moreover, worldwide, this topic is part of the Science, Technology, Engineering and Mathematics (STEM) primary school curriculums within the human physiology contents (*e.g.* understanding life systems : identify major systems in the human body - musculoskeletal, digestive, nervous, and circulatory systems - and describe their roles and interrelationships [e.g. 7; 18]).

However, accessible and pedagogical learning material that is suitable for children is lacking. Then, at school, teachers rarely focus on the workings of the brain during their classes. As a result, although the brain is one of the organs of the human body that children often name instantly when asked (along with the bones, the heart and the stomach), how the brain actually works remains comparatively poorly understood [46]. Children's conceptual models of the biological and functional aspects of the brain reveal rather a naïve, piecemeal understanding. Such representations can be seen through the initial views expressed by the pupils at the beginning of this study (see Figure 3).

Learning the physiological functions of the brain is very challenging for children. Indeed, the functioning of the brain is imperceptible to the senses, it remains intangible [65]. Unsurprisingly, these results show that the brain is essentially seen as the seat of intelligence and emotions by the children. Brain structure and brain functions such as motor control and sensory perception are all but unknown. Until they have reached the formal operational stage (*i.e.* final stage of the Piaget's development theory that begins at approximatively age twelve; stage at which learners have the ability to think in an abstract manner [50; 51]), children require concrete, physical and visual aids to build knowledge. As for many fields in Sciences, it appears that a realistic, attractive, three-dimensional model, which offers possibilities for interaction and which facilitates observation and manipulation, could be of value to this usership for learning about physiology [6; 44; 69; 73]. These characteristics are intrinsic features of TUIs. Thus, a new generation learning aid like Teegi might be able to cater for the real needs in terms of relevant pedagogical material.

Tangible Interfaces and Brain Functions

In computer science and HCI, the vast majority of applications target the use of physiological signals as novel input methods for HCI. The same is true for the field of Brain Computer Interfaces (BCIs), in which brain activity is used to send commands to a computer without moving a muscle [76]. However, besides specialized tools which allow medical students and experts to represent internal organs using imaging techniques such as ultrasonography, MRI (Magnetic Resonance Imaging) and EEG, very few interfaces are designed for novice users who want to learn how the brain works. Thus, both the tangible interface developed by Panchaphongsaphak et al. [47]– which combines a physical model of the brain with a virtual reality display – and the augmented reality representation of EEG activity designed by Mercier-Ganady et al. [41] remain inaccessible to the general public, particularly for children. Uğur [64] and Williams et al. [75] used wearables and actuators in order to display physiological signals in an intuitive manner. However, the information displayed concerned the expression of feelings, and was not explicit per se. A few tangible interfaces have been designed for scientific outreach and introspection (e.g. [23; 44]), but

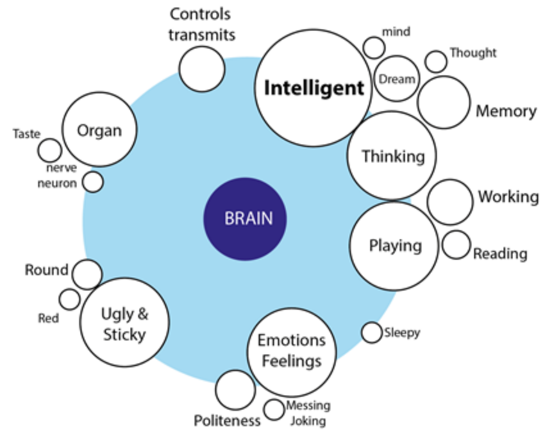

Figure 3: A depiction of the initial representations of the children who took part to the study. Children were asked to name 5 words that occur to them when they hear the word "brain". Circle sizes are related to the number of occurrences.

to our knowledge Teegi is the only interface designed to explain phenomena related to brain function.

PEDAGOGICAL POTENTIAL OF TEEGI

Teegi meets pedagogical needs. However, for quality learning to be encouraged, and according to Instructional Design (ID) principles [22; 61] and frameworks [e.g. 31; 32; 43; 54], we identified that a learning material provided to learners must:

Factor 1 : be usable and attractive;

Factor 2 : enable the learner to identify the contents and/or the tasks to learn (i.e. help the child to be conscious of what and/or how he/she learns);

Factor 3 : make intended learning outcomes effective (i.e. efficient);

Factor 4 : stimulate academic motivation (i.e. not only to interact with the system but also to learn with it).

With the aim to estimate the pedagogical potential of Teegi with pupils in formal/informal contexts, we inspected then these general four factors.

Limitations and methodological choices

These four factors, though, depend on the context of use (*e.g.* at school, at home or in lab conditions). For example, a learning support could be perceived as unattractive and discouraging when used at home. At home, the learning tasks could be more associated to the world of school by the children. Therefore, in order to assess a CCI designed to be implemented in school setting, the child user must be treated as a learner, not as a single user (see [15]). Children should be fully engaged as school pupils, and so the environment should resemble, as closely as possible, to a standard formal learning situation. Thus, we chose to conduct our assessments in the "ecological context of school" [11].

Yet assessing the effectiveness of a computing environment in a real-life context is extremely complex. This is notably due to the difficulty to conduct the study with enough participants, which requires to work with several classes with comparable features. It is also due to the lack of traditional learning materials that mobilize similar contents and tasks than the TUIs do. Hence, it is not always possible to compare TUIs with more "standard" approaches. In our case, as mentioned previously, there is a shortage of relevant learning material.

In this context, it is clear that we attempt to estimate a pedagogical potential in use conditions, rather than trying to determine an absolute measure of the effectiveness of the interface. Therefore, we chose to design a multimethod approach, qualitatively driven, to collected complementary observations and learners' perceptions, as recommended by *e.g.* [53; 64; 67]. Our goal is to i) estimate Teegi's impact on the 4 factors mentioned hereinabove crossing HCI and learning sciences; ii) counteract the aforementioned difficulties associated to a real context study and to a lack of traditional support.

Means and methods

To conduct our testing in real-life conditions, a half-day long school outing was organized on the topic of "Coding and Robotics". This topic was deliberately different from the topic that Teegi is designed to target to avoid biasing the assessments. This school outing was designed and carried out in collaboration with postgraduate Education and Instructional Design (EID) students of the Université de Lorraine, France. The workshop took place in a living lab dedicated to education tools situated in Metz, Canopé 57 France. The setup of the learning area in the living lab space and the teaching scenario were designed to resemble a science workshop as held in classes and in science museums. To maintain a sufficient level of control, environmental (*e.g.* teacher effect [45], classroom atmosphere, heterogeneous audience) and institutional (*e.g.* respecting academic pace, the curriculum and deontological rules such as providing all pupils with equal access to knowledge) issues were controlled as strictly as possible. Hence, pupils took part in three different workshops, including one with Teegi in groups of 3 or 5/6 pupils. Each workshop duration was 30 minutes and was conducted by EID students. Pupils were not allowed to work for more than 2 hours in total, in accordance with the rules concerning class hours and playtime/toilet breaks. The activities fitted within the new French STEM curriculum for 7-11 year olds [18; 19]. All the pupils took part in all the activities organized during the half-day outing.

Participants

The involved class comprised 29 pupils (see Table 1), who were 9.71 (STD 0.85) years of age on average, including 17 girls and 12 boys. Among these pupils, 3 girls presented different degrees of cognitive impairment. With academic delays ranging from 1 to 3 years, they had difficulty writing and understanding instructions. One of the boys had attention deficit hyperactivity disorder-like symptoms, but other than the presence of his teaching assistant, he required no further adaptations. With the help of the teacher, particular care was taken to include the children with disabilities. Finally, the groups were mixed-gender apart from two groups comprising only girls (Groups A & F, Table 1).

Assessment Methods

Considerable thought was given to select appropriate questionnaires and assessment methods. Standard questionnaire-based assessments, the reliability of which is often debated [28], begin to show their limitations when used with such young participants [37; 38].

Beginning of the session			9h00	9h15	9h30	9h45	10h30	10h45	11h00	11h15	Total
Participants characteristics	Group		A	B	C	D	E	F	G	H	8
	Average age		9.7 std=1.04	9.3 std=0.57	9.3 std=0.57	9.7 std=0.58	9.3 std=0.57	11.3 std=0.57	9.5 std=0.50	9.7 std=081	9.7 std =0.85
	Pupils/Gr	*Nbr. of pupils*	3	3	3	3	3	3	5	6	29
	Pupils with disabilities		-	-	-	-	**1**	**3**	-	-	4
	Girls		3	2	1	2	1	3	3	2	17
	Boys		0	1	2	1	2	-	2	4	12
Target know-ledge	Causal effect	*Nbr. of pupils*	1	2	2	3	1	-	2	-	11
	Activated areas		2	1	1	2	2	1	3	4	16
Observable pupils' behaviors	Manipulate	*Av.% of the session duration/pupil*	32.76 std=2.69	29.57 std=5.11	40.75 std=2.39	27.67 std=6.60	14.66 std=1.98	27.11 std=7.19	47.55 std=5.54	66.31 std=8.08	39.76 std=17.45
	Observe		27.78 std=3.49	22.80 std=10.01	10.87 std=5.86	10.11 std=7.25	5.05 std=3.40	7.30 std=1.14	41.03 std=4.41	52.40 std=12.41	26.60 std=19,29
	Fill the worksheet		41.34 std=2.81	42.36 std=6.66	39.58 std=5.41	35.30 std=10.77	44.32 std=3.04	12.52 std=1.68	28.34 std=7.38	13.77 std=7.17	30.02 std=13.66
	Drop out		-	-	2.06 std=1.58	0.87 std=1.18	1.26 std=1.26	1.10 std=1.91	1.04 std=0.66	3.52 std=1.65	1.46 std=1,64
	Indicate an active zone	*Av. nbr of actions /pupil*	7.33 std=3.51	7.67 std=3.51	7.00 std=6.08	7.33 std=4.04	1.67 std=2.08	4.00 std=4.58	3.00 std=3.54	1.16 std=1.16	4.38 std=4.06
	Manipulate an interactive zone		11.00 std=8.72	11.00 std=7.21	26.00 std=2.00	21.00 std=7.81	13.00 std=5.57	33.00 std=12.12	7.80 std=4.38	8.5 std=4.27	15.00 std=10.31

Table 1: Characteristics of each group of pupils who tested Teegi in a real-life context, associated with the number of pupils who reached the targeted knowledge and with the main behaviors observed when interacting with Teegi.

Indeed, many commonly used user-experience and interface usability scales, such as the *Standard Usability Scale* [63], are inappropriate for children. Besides their subjectivity, the main issue with these questionnaires arises from the complexity of the instructions and from the vocabulary that they use (*e.g.* words such as "system", "functions" are not understandable for children). Children have poorer vocabularies and less experience than adults. This makes it difficult for them to describe and express their perceptions. Additionally, rare are the validated questionnaires for children. Therefore, in an attempt to overcome these obstacles, we chose to gather the perceptions and the representations of the user-learners through oral, written and pictorial methods, and taking into account Read et al. [53] guidelines. In all tests, EID students helped to understand the instructions. Pupils were not obliged to give written answers when requested, so as not to penalize children with disabilities and pupils who were ashamed of their poor mastery of written French. Furthermore, we chose to select tests from the fields of HCI and learning sciences that we believed to be suitable for children (*i.e.* not too demanding) and adapted to the four factors that promote learning (see also Table 2).

- The Rapid Desirability Testing [26] (RDT): The aim was to gather orally the pupils' first impressions and perceptions regarding the esthetics of the system, concerning its physical characteristics, its visual qualities and its shape. This 5-minutes test allowed us to assess the halo effect and the desirability of the system [e.g. 60; 62].
- The Attrakdiff questionnaire [25] was chosen to assess the usability and attractiveness of the interface. We used the French short version of the questionnaire that contains 10 simple items [35]. This questionnaire evaluates the perceived pragmatic (4 items) and hedonic (4 items) attributes of the interface, as well as its overall attractiveness (2 items), using a 7-point semantic differential scale. An extra item was added asking pupils whether they found Teegi motivating or discouraging. This short questionnaire was pre-tested in a school-based study and was shown to be understandable for pupils [10].
- The test of motivational value of a learning activity (MVLA) was also used. This test, in French, was designed by Viau [66] to assess primary school situations. This questionnaire is based on a 4-point Likert scale. It assesses the standard criteria related to extrinsic motivation according to the model of motivational dynamics [68]: clear, diverse, significant, challenging activities, which confer responsibilities and demand cognitive engagement, which enable collaboration, which last a sufficient amount of time and are authentic. Here, the goal was to assess the motivational levers provided by the learning activity conducted with Teegi. We excluded the results of the last question due to the difficulties for children to perceive the authenticity of this type of activity with a TUI.
- Pupils were also asked to depict their representations in pre-test and post-test drawings. Using drawings of pupils' conceptualizations is a classical method for analyzing conceptual change when teaching science [e.g. 1; 3; 4; 71; 72]. Conceptual change occurs when pre-existing conceptualizations are modified due to learning, thus changing the pupil's representations [70]. The aim of this test was to estimate Teegi's impact on learning goals.
- Two open-ended questions within the post-test with written answers allowed us to gather subjective feedback after the test: "*What does Teegi help you learn"* and "*What are your comments on Teegi?*". Lexical similarity between the texts was analyzed (48 texts. 5 lines long on average) using IRaMuTeQ [52]. This helped us to determine how pupils perceive Teegi, and what he embodies in terms of intended learning outcomes.
- Furthermore, pupils were given observation sheets to fill out during the workshop with Teegi. These allowed us to ascertain whether all pupils had correctly identified the interactive parts of the system, and to study the nature of their observations. They were also asked to answer an open-ended question: "*More specifically, what happens?"*. This allowed us to gather information concerning how well pupils had perceived the cause and effect relationship between their manipulations and the system's response.

In order to overlap all the factor to appraise, this declarative data was also combined with the children's effective implication in the activity. The latter was assessed by analyzing pupils' user behavior. To do so, two trained coders (one is researcher and teacher trainer in STEM, one is researcher in HCI ergonomics) used The Observer XT 14 (Noldus. Info Tech. Wageningen. Netherlands) to perform video-assisted analysis based on a behavioral assessment grid comprising 3 categories:

1. interactions with the interface (*i.e.* moving/touching Teegi's interactive parts as head, hands, feet, glasses; Other Teegi's body parts; lifting him up; turning him around, stroking or tickling him)
2. activities carried out with Teegi (*i.e.* observing; pointing; manipulating with the aim of checking something: inquiring; manipulating aimlessly helping a classmate; playing; filling the worksheet, others such as chatting; listening or reading explanations)
3. involvement in the tasks (*i.e.* number of manipulation and duration; duration of drop out; expression of emotions: smiling, laughing, complaining, fulfillment).

Factor	**RDT**	**Attrakdiff**	**MVLA**	**Pre & Post Tests Rep. Drawings**	**Post-Test perception**	**Observation Sheets**	**Video analyses**
1	✓	✓					✓
2					✓	✓	✓
3			✓	✓		✓	
4	✓	✓	✓				✓

Table 2: Overview of the tests chosen to assess the pedagogical potential of Teegi. All the 4 factors are overlapped by three or four tests in accordance with a multimethod approach.

Describing the test session

One week before the user test, pupils completed pre-tests relating to their representations of the human brain (*i.e* specific vocabulary known - see Figure 3- and representation drawing). On the day of the test, the pupils were given a short presentation of the workshops. During the first part of the morning, six groups of 3 pupils interacted with Teegi. The group comprising the three cognitively impaired girls (Group F) were provided with suitable instructions and assistance. In the second part of the morning, two largest groups (one of 5 and the other of 6 pupils) used Teegi (see Table 1). Audiovisual recording was performed using two GoPro cameras mounted on tripods placed in the corners of the defined learning area. They were rarely noticed by the children and quickly forgotten. Teegi was placed in the middle of an ordinary table in a distraction-free area that was separated from the other workshop areas. Upon entering the area, pupils would find themselves standing just in front of the table (see Figure 4).

All test sessions followed the same scenario. It is important to notice that the intended learning outcome was never stated. Each session began with the Rapid Desirability Test. Pupils were asked "*This is Teegi. what do you think of him?*". Next, during the first five minutes of exploring Teegi, an experimenter helps the pupils to discover how Teegi operates. During this period, Teegi would move automatically, the experimenter would also answer the pupils' questions, and hand out and explain the observation sheets. Next, pupils could observe, manipulate and fill in their observation sheets for 10 to 12 minutes without guidance. Because the presence of an adult being legally required to guarantee pupils safety, the experiment administrator stayed discreetly in the area throughout the session but did not intervene unless she was asked a technical question by a pupil. After these 15 minutes, the next group was shown in to carry out the same user tests. The previous group was then taken to a different area by EID students, who gave them instructions on how to complete the Attrakdiff and MVLA questionnaires. They were asked to sit far enough apart so that they were unable to see their classmates' answers. Less than 15 minutes were required to fulfill the two questionnaires. Finally, the post-tests were completed in the afternoon, in class, more than two hours after the end of the last test session, and after the midday break. This was done to assess short-term learning.

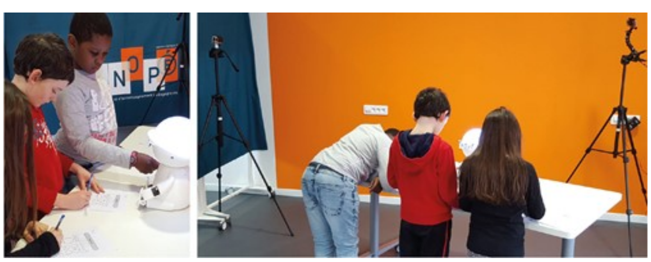

Figure 4: Illustration of the position of the pupils, of Teegi and of the video capture system for a group of 3 children (Group E) during the test session.

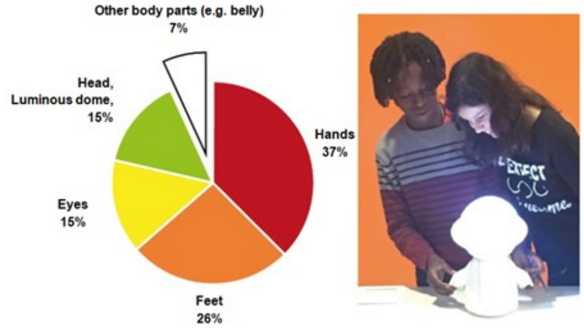

Figure 5: **The parts of Teegi that were manipulated by the pupils. Left: Pie chart showing manipulation of each body part, expressed as a percentage of total manipulations (number of manipulations of the body part / total manipulations x 100). Right: A typical example of observable collaborative manipulation. One pupil manipulates while the other observes; the third kid is filling the observation sheet.**

RESULTS AND DISCUSSION

Factor 1: Usability and attractivity of Teegi

Operability

The analysis of observable behavior using video recordings reveals that pupils were quick to appropriate Teegi. Besides the time spent with the experimenter at the beginning of the session (mean duration of the functioning presentation 2.45min STD= 1.29) no more time was required for pupils to understand how Teegi works. The pupils never asked for help except on two occasions: once to change the batteries (Group F), and once to reattach a hand (Group H). No unexpected manipulation, no tiredness nor stress signs were observed. The pragmatic qualities (PQ) of the interface (Question 1 to 4 on Figure 6) using the short Attrakdiff questionnaire revealed that Teegi was seen by the pupils as simple, clear and practical (average score for PQ: 1.49 STD = 1.65, on a range from -3(min) to 3(max)). This tends to show that the interface is *usable*.

Types of use

During the all 15-minutes with Teegi, pupils alternately manipulate (39.76% of the session duration, STD=17.45) and observe (26.60% of the session duration STD= 19.29) the interface (see Table 1). These two behaviors are significantly correlated (Pearson correlation coefficient manipulate/observe $r=0.886$ $p<0{,}001$). Pupils tended to perform lots of brief manipulations (each lasting 3-10 seconds) and to observe the consequences (see Figure 5). They filled their observation sheet during 30.02% of the session duration on average (STD=13.66). Pupils were very rarely distracted and were seldom disengaged from the activity (1.46% of the session duration, STD=1.64). However, we observed a clear task alternation; alternation also observed between the children. Indeed, when one was manipulating or observing Teegi, another one was filling the worksheet (Pearson correlation coefficient between durations to fill/manipulate $r=-0.508$; $p=0.005$; and to fill/observe $r=-0.670$; $p<0.001$) (See Figures 4 & 5).

The nature and the rate of individual manipulations were not significantly influenced by the age, the gender nor the disabilities of the child. Interestingly, the group size significantly influenced this rate (one-way ANOVA F=12.89; ddl=28; p<0.001) by comparing children from small groups to the ones from larger groups (i.e. 5 and 6 children). Video analyses indicate that in the 6 small groups, pupils collaborated [12]. They turned to manipulate Teegi with a coordinated effort, and carefully observed the results of their classmates' manipulations (See Figure 5). Pupils often pointed at (nbr. of pointing tasks/session/pupil = 5,83; STD=3,97 in small groups, and 2,08 STD=2,35 in large groups) to help their classmates see activated brain areas (See Table 1, Groups A to F). Otherwise, they took notes on their observation sheets (See Figure 4). This way of working enabled these children to take part equally in the activity. On the other hand, in the two largest groups G and H (See Table 1), simultaneous manipulations by two or three pupils were more frequent. Children were unable to wait for their turn, especially in the group G. Since several Teegi's body parts were being manipulated simultaneously, several brain areas lit up at the same time. Moreover, the tasks were distributed *i.e.* pupils remained either manipulators or observers, and then the average manipulation rate per children decreased.

Attractiveness

The pupils' answers at the RDT mainly reveal positive emotions: "*He's brilliant!*", "*Oh. he's soooo cute!*", "*He's really, really sweet*". None of the children seemed frightened or repulsed by the interface. 3 children immediately greeted Teegi either with a wave or a "*Hello!*" or a "*Hi there little thing*". What is more, 6 children remarked that "*He really looks like a human*". 8 pupils said "*He's smiling!*", or "*He's smiling with his eyes*" when Teegi blinked, even though he has no mouth (See Figure 2). The pupils' first impression was then positive, and their first reactions tended to be very similar to those that can be observed during human interactions. Next, all pupils kept positive attitude without ever showing signs of exasperation or frustration. After the session, as declared in the Attrakdiff, Teegi was considered *attractive* (Total average score: 2.36 STD = 1.39; see Figure 6) and particularly captivating (Total average score: 2.68 STD = 1.04). The perceived hedonic qualities (HQ) of Teegi, (HQ = average sum of Q5 to Q8 scores; a neutral score = 0; a max score = 3; a min score =-3) were rated favorably (Average score for HQ: 2.20 STD = 1.39). The HQ of the system reflects the ability of the product to provide emotional stimulation. This perceived attractiveness shows that Teegi was *"desirable"* in this type of use. Even if the differences are not statistically significant, the HQ results were higher for girls than for boys (Girls' average HQ score =2.32 STD=1.08 and Boys' HQ score= 2.00 STD = 1.68); Teegi stimulated girls' interest in a traditionally male field of science and technology [29; 36]. Teegi generated similar responses regardless of cognitive ability, and then stimulated positively all children without discrimination.

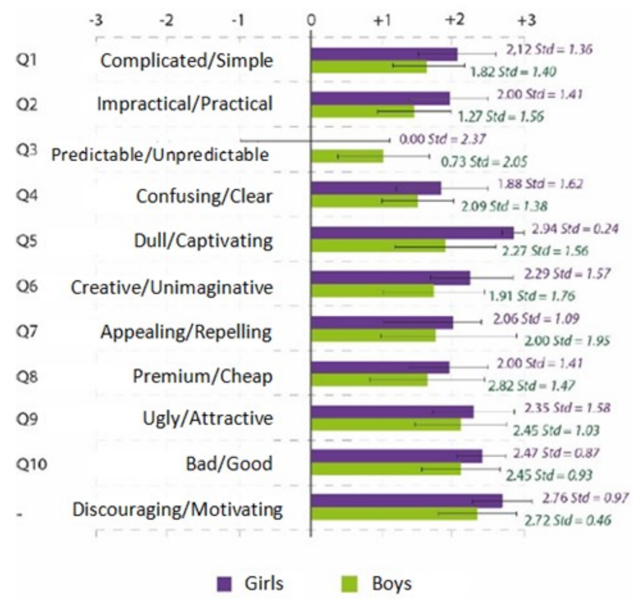

Figure 6: Results of the short version of the Attrakdiff questionnaire ("*After using Teegi, I think he is …*") according to the gender of the respondents. The assessment is based on a 7-point semantic differential scale (*i.e.*, -3: complicated, +3: simple). For analysis, answers were given the following values: -3, -2, -1, 0, 1, 2 or 3. Q1 to Q4 evaluated pragmatic qualities (PQ), and Q5 to Q8 evaluated hedonic qualities (HQ). Q9 and Q10 assessed overall attractiveness of the system (according to [35]). The last item concerned the additional question on motivational attribute.

Factor 2: Effects on learning tasks and content to learn perceptions

In order for a learning to be effective, the learning outcomes, the task to perform and the target field of knowledge should be made explicit to the learner [22; 33]. In our approach, pupils were deliberately uninformed, both before and during the session. This allowed us to see whether Teegi was intrinsically explicit as a pedagogical model, that is to say whether or not the learning contents were self-evident, *i.e.* tangible, for children.

Learning tasks expected during the session, in accordance with inquiry-based science learning [42; 80] promoted by the French curriculum, were to inquire which brain zones are involved in vision and motor control by manipulating interactive parts of Teegi. Analyses of video recording indicated that 93% of the 5 to 40 individual manipulations per session (Average nbr/pupil/session =15.00 STD= 10.31 – See Table 1) corresponded to a manipulation of an interactive zone (see Figure 5). These zones are then recognizable by children. The analysis of observable activities brings to light that observation, manipulation prevailed (see before). However, individual pupils' interactions with Teegi tended to be goal-oriented. They varied in function of on what child intended. Inspired by Markopoulos et al. [38], we propose to categorized them in three classes (See Figure 7).

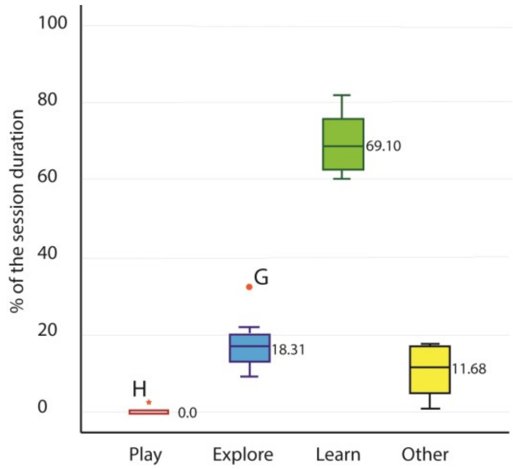

Figure 7: Comparison of the boxplots of the 4 oriented tasks involved with Teegi during the session duration. Other tasks correspond to all the tasks not directly related to Teegi.

The child acted with Teegi as

- a *Player* when tickling Teegi, playing with Teegi like a doll or a robot;
- an *Explorer* when turning Teegi around quickly, lifting and/or inspecting him, interacting with him to understand how he works but without any apparent learning goal;
- a *Learner* when inquiring, trying to understand by manipulating, checking something and filling the worksheet, observing the consequences of his/her manipulations.

The fact that Teegi resembles a doll or a robot could have led the children to be more playful [37], even in school context. But, only one pupil exhibited player behavior (Group H, see Table 1 and Figure 7). All the pupils inquired with Teegi to learn and discover brain functions during more than 61% of a session duration (min duration = 60,11% of the session duration; see Figure 7). The learning tasks to perform seems to be identifiable by all the children in this context. Pupils behaved as explorers only during the discovery phase with the experimenter, excepted in group G. In this large group, pupils took more time to inspect Teegi's functionalities.

The lexical analysis of the answers to the post-test questions "*What does Teegi help you learn?*" and "*What are your comments on Teegi?*" (23 respondents out of 29 pupils) reveals that 69% of the respondents correctly identified and formulated the learning goal: "*Learn a bit more about the brain and how we can control our brain*" (red field on Figure 8). These 16 of 23 pupils were also those who produced an entirely correct schematic representation of the brain (see below). However, a second semantic field reveals that for 7 pupils the learning goal was related to technology (orange field on Figure 8). Although for some pupils (5 of 23) the two goals overlapped (*e.g.* "*See a robot that teaches you how the brain works when you move*"). The learning goal was then not explicit for all the pupils and was somewhat confused with the goal of the entire outing.

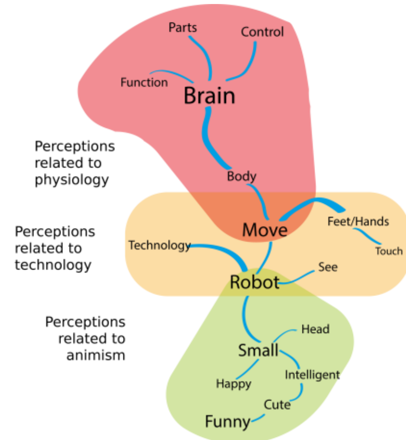

Figure 8: Results of the lexical similarity analysis (using IRaMuTeQ [52]) showing the relationships between the words used in the post-test texts. Results reveal that pupils perceived three main areas of knowledge: 1) brain function (red); 2) technology (orange). and 3) a humanized character (green). Font size is indicative of word occurrence. Link thickness is indicative of how many times the words were used together.

Furthermore, Teegi's cheerful and resemblance to a human sparked several questions during all the session. Thus, it comes as no surprise to find that a third semantic field (green field on Figure 8) contains words relating to human personality traits (e.g. Teegi is "*funny*". "*intelligent*") formulated by 13 of the 23 respondents. As noticed for avatars [2], the Teegi's anthropomorphic features and behaviors could explain why children react socially to this TUI. However, this seems to reactivate animistic and realistic thinking in children as some times observed when they interact with robots [5]. This could lead to a certain confusion regarding the concept of Life, and the pupil's understanding of the physical world.

Factor 3: Learning effectiveness

The pre-test and post-test drawings were analyzed considering the:

i) ability to represent the brain as a functional organ;
ii) awareness of the fact that the brain is structured and that specific areas are involved in specific functions;
iii) understanding that there is a cause and effect relationship between movement and brain activity.

28 of the 29 tests were usable (one child was absent during the post-test session). After having interacted with Teegi, and after the lunch break, the pupils' post-test depictions of the brain had considerably changed compared to the pre-test drawings (See Figure 9). Indeed, 57% of drawings were schematic representations (compared to 18% for the pre-test), revealing that their mental images were now more functional than factual (i.e. anatomical) or metaphorical. The number of children who were unable to produce a graphic representation of the brain (i.e. uncharacterizable - Figure 9) decreased considerably. 23 out of 28 (including 2 of the 4 pupils with disabilities, see Table 1) located some if not all of the observed brain areas on their drawings (*i.e.* the brain

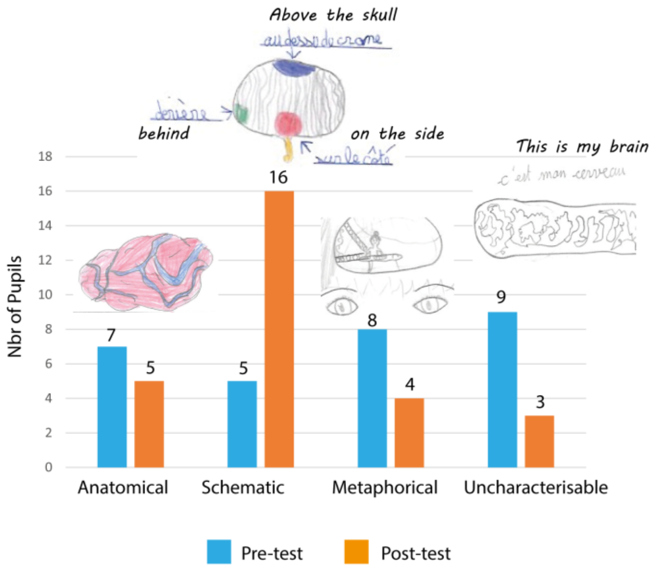

Figure 9: Different types of pre- and post-test representations of the brain, associated with examples of children's drawings.

areas involved in moving the hands and feet and in vision, correctly separated from and located in relation to one another), among whom 16 children produced totally correct, labelled schematic representations. Interestingly, these children are the same that correctly identified the learning contents in the open-ended question (see above). Moreover, 8 pupils felt it necessary to orient their drawing with labels indicating directions on their schematic representation (*e.g.* back of the head, right hand side – see schematic representations on Figure 9). It shows that these children were struck by the location of active brain areas. In comparison, none of the pupils had been able to locate functional areas during the pre-test, and only one child had used labels to orient his drawing. Noticed that only 9 pupils commented on the fact that movements on one side of the body activated areas on the opposite side of the brain. There was no correlation between pupils' gender and the types of drawings that were produced at pre- or post-tests. However, the quality of brain representation produced during the post-test seem to be influenced by the number of manipulations. The pupils that manipulated a lot performed well at the post-test. Those ones were mainly those who had done the activity in groups of 3 (except for the pupils with disabilities - Table 1). Moreover, most of 11 pupils whom perceived the cause and effect relationship between movements and specific brain areas activation were in the small groups. Then, the group size might have influenced the learning quality. This point should be the focus of more attention in the future.

Factor 4: Motivational Impact

Academic motivation encompasses everything that makes pupils engage in a task, behave in a way that helps them learn and persevere in the face of difficulties [67]. The results of the Attrakdiff test show that Teegi was judged as very motivating (2.75 STD = 0.81; a max score = 3; see Figure 6). Moreover, video recording analyses indicated that pupils showed signs of enthusiasm and eagerness to interact.

Teegi's esthetic qualities and his potential for providing emotional stimulation enhanced his attractiveness. This seems to have an impact on children's desire to learn. Associated with these results, the MVLA test provides a more holistic view of the effects of the session with Teegi (see Figure 10). The motivational test results reveal that, learning with Teegi, in the present conditions, had a positive effect on 5 of the 9 factors that could help to promote academic motivation. The activity was considered long enough (3.21 STD = 0.89; a max score of 4 = always) and clear enough (3.48 STD = 0.69; a max score of 4 = always). Besides these elements that are totally extrinsic to Teegi, pupils valued being:

i) allowed to collaborate with their classmates throughout the activity (3.38 STD = 0.74);
ii) enabled to make choices during the task (2.9 STD = 0.77);
iii) abled to do tasks that they considered varied/different (2.83 STD = 0.85).

These effects, which seem induced by Teegi's intrinsic characteristics (*i.e.* interactive, tangible, easy to use; remember that no specific instruction was given to children), supported pupils' motivation besides a novelty effect and its attractiveness. Interactions with Teegi in a social environment had a positive impact on motivation. And yet, the knowledge mediated by the interface was not of any special interest to the pupils. Responses to the item "*The workshop with Teegi was related to my everyday interests*" were rather neutral on average (2.62 STD = 1.17 – orange bar on Figure 10). Teegi usability did not restrict autonomous choices, and then could support the learner's sense of task controllability and of their own ability to perform the task. However, the notions of cognitive engagement, learning issues and interdisciplinarity, which are necessary for motivation and perseverance, were here poorly evaluated (see yellow bars on Figure 10). Working with Teegi was not challenging (1.93 STD = 1.14 – under a neutral score). Teegi is not too demanding, probably because this TUI only offers a limited number of possible interactions. That opens new opportunities for further developments.

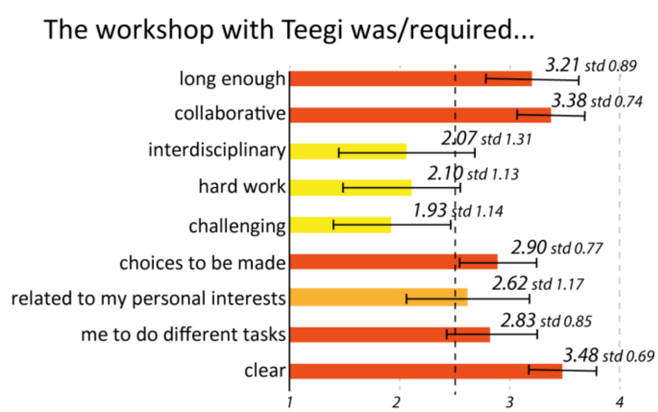

Figure 10: Average results for the 9 items of the motivational value assessment for the session with Teegi. 1 = Never. 2 = Rarely. 3 = Often. 4 = Always. Min score = 1; neutral score = 2.5; max score = 4.

Discussions

The results show that Teegi was easy to appropriate, usable and reliable for the children who took part in this study. Besides the pragmatic qualities of the system, its appearance and the associated halo effect had an impact on i) its attractiveness, ii) pleasure of use and iii) satisfaction derived from using it. Teegi's esthetic qualities, anthropomorphic and cheerful appearance generated positive emotions for all the pupils, from the moment they first saw him and throughout use. In this case, it helped to include the pupils with disabilities, and to stimulate girls' interest in the traditionally male field of science and technology [29; 36]. This also impacted on children's motivation and desire to learn. Teegi's design and functionalities also geared towards helping the pupils to interact with the content to learn, and can be seen as levers that can promote active, voluntary learning [40; 49]. After using Teegi for as little as 15 minutes, the majority of the pupils had gained valuable knowledge related to the learning outcomes. Teegi has then a real and considerable pedagogical potential.

However, our design choice based on a realistic and interactive three-dimensional model, induced collusion between humanity and an animated technological object for some children regarding the human brain functions. This uncertainty linked to Teegi's intrinsic learning goals could have hinder their acquisition of scientific knowledge. This need to be clarified by the teachers or mediators in future uses. The results also highlighted the need to help children to pay more attention to the cause and effect relationship, given the fact that not enough children had noticed it by using Teegi without external guidance. Finally, children appreciated that Teegi enabled them to collaborate. However, in the present conditions, the social interactions oriented towards collaborative tasks were effective in the smaller groups. This endorses the suggestion that tangible interfaces support collaboration [e.g. 13; 30], but added certain qualifications. Indeed, when used in larger groups, Teegi rather generated a predominance of individual interactions, of tasks distributions, and of simultaneous co-operations by two or three children that had consequences on learning quality. The work processes affected then the pedagogical potential of this TUI by influencing the quality of the pupils' observations and tasks.

CONCLUSION

The results of this multi-methods quality driven study, conducted in a real context of use, reveal that Teegi affected the cognitive, affective and conative (*i.e.* mental processes that relate to intending to do something) dimensions of the "*learning proneness*" [8] of most pupils by acting on their will to learn, their ability to learn and their knowledge of how to learn. All these parameters evidence the pedagogical potential of Teegi to enhance the understanding of brain functions in this type of school context, also in a non-discriminant manner. Moreover, our results supply further evidence supporting the use of TUIs as learning tools. However, and whatever the TUI's pedagogical potential, they indicate that pedagogical awareness remains needed to enable quality learning in real context of use (*e.g.* to help the child to identify the learning contents, and to set up adapted work processes). This approach provides also food for thought regarding possible improvements to the current version of Teegi. Also, to make Teegi more challenging, we are considering adding new features such as a camera near Teegi's eyes. The optical flow could be used to enhance the interaction. For instance, one could observe the different responses in terms of brain activity to seeing different images (*e.g.* vertical vs horizontal lines), or images in different positions relative to Teegi's eyes (*e.g.* to his left, above him). The groups of neurons involved, and thus the display on Teegi's head, would vary accordingly. Moreover, adding microphones near Teegi's ears could allow users to see that different brain areas are activated when we hear a noise compared to when we hear naturel language for instance.

This study also shows that the methods we used (*i.e.* the user experience tests, the pedagogical value assessments, and the behavioral analyses) were suited to the present population. Moreover, connecting various user-tests from the fields of HCI and learning sciences to behavior and pedagogical data sampling (*i.e.* MVLA, drawing comparison, and the lexical analysis) was relevant. It enabled us to overlap by numerous modalities each of the four factors to assess. It mitigates results if provided by user-tests only and many pedagogical information would have been inaccessible if user tests alone had been administered, or if the study had taken place in laboratory conditions. It covered then in a more holistic and objective manner the assessment of pedagogical use of our interactive system in school context. Even if, this multimethod approach is time consuming and need to be duplicated, many limits have been exceeded when investigating a children population in ecological context. We hope that, more than helping us in the design improvement of Teegi, this study opens future methodologies to evaluate the pedagogical potential of interactive systems in real context of use, and forward facilitate their integration in classrooms.

ETHICS STATEMENT

This experiment was conducted after having obtained permission from the headmistress of the school and from the pupils' teacher. The legal representatives of the pupils also gave their informed consent, thereby allowing their children to take part in the study and giving us permission to film them and take photographs. Finally, a specific authorization for use of images was given and was strictly observed.

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SELECTION AND PARTICIPATION OF CHILDREN

In this study, 29 children, from 9 to 11 years old, coming from a French primary school, were involved. See more descriptions in the paper. This class was selected because it is at the national standards towards social and occupational categories of the parents, and also includes impaired students. All the participants and their parents provided informed consent for participation in the study and the inclusion of photographs. It was explained to both parties that data would be used for research and communication purposes only, and that anonymity will be kept. See also Ethic statement.

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